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Real Time Diagnosis in Wind Energy Conversion System

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Abstract

The current paper presents an FDI (Fault Detection and Isolation) technique applied to the Doubly Fed Induction Generator (DFIG) of a Wind Turbine (WT). The method is based on the use of a Generalized Observer Scheme (GOS) using a Kalman filter. The fault localization is performed by the Page-Hinkley's test. The whole procedure is validated using a numeric simulator, then a real benchmark emulating a wind turbine. Finally, real time tests are performed to allow real time validation.

Keywords

Diagnosis; Wind Turbine (WT); Doubly Fed Induction Generator (DFIG); Generalized Observer Scheme (GOS); Page-Hinkley's Test; Real Time Test

Introduction

The exhaustion of fossil energy resources and environmental problems caused by gas emissions, allow the development of renewable energy sources, and offer the possibility to produce electricity properly on the condition to accept its random fluctuations. Some of these renewable energy sources are:

- Hydraulic energy, the first source of renewable energy for electricity production. The world power installed reached 740 GW, when the annual production is 2.7 .1012 kWh. The Small Hydro Power (SHP) plants are attractive due to its distributed production. It is, by definition, powers lower than 10 MW(range goes from 0.5 MW in Luxembourg to 50 MW in Brazil). They are considered as new solutions to produce energy from renewable sources. In France, even if large hydropower is saturated, there is still potential for development of SHP, 3500 units with maximal power of 1700MW and about 7.109 kWh per year (Multon, Robin, Ruellan & Ben Ahmed, 2004). In this context, we can also talk about wave energy which is also a renewable energy source studied by (Clément, McCullen, Falcao, Fiorentino, Gardner & Hammarlund, 2002) and (McCormick, 1981).
- Solar photovoltaic, the direct generation of electricity from light associated with enormous solar energy resources is one of the most promising principles of power generation. Photovoltaic conversion is static, offers total quiet operation and allows a high reliability.
- Solar thermodynamic, legacy solutions to fuel power plants, solar power plants can operate directly heat radiated by the sun to transform water into steam. An intermediate heat storage allows smooth production. Even with the low thermodynamic efficiencies of steam turbines (about 30%), an annual production of 4.106 kWh with a peak electrical power of 3 MW can be considered.
- Geothermal power, in some favorable areas, deep water at high temperature is found by drilling. In the range of 150°C to 350°C, it is called high geothermal energy. Water is pumped to the surface and passes through heat exchangers, steam produced is then used as in conventional thermal power plants.
- Wind power whose potential is quite important not to replace existing energy but to answer to the growing demand. After centuries of evolution and further research in recent decades, several countries are now resolutely turned towards the wind energy. However, several reasons can affect the performance of a wind turbine (Hau, 2006) (Trujillo, Bingöl, Larsen, Mann, Kühn, 2011). It can be wind speed, wind turbine location, blades (Sørensen, Schreck, 2011). The performance optimization has attracted the attention of many researchers (Mirecki, Roboam, Richardeau, 2007) (Jauch, Matevosyan, Ackermann, Bolik, 2005). This

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involves finding an adequate model of the wind turbine (WT), to detect errors that may impair its proper operation in order to guarantee its control (Hazra, Sensarma , 2010) (Todeschini, Emanuel, 2009).

To approach their true dynamics, several wind turbine models have been developed (Soliman, Malik, Westwick, 2009). There are two classes: analytical and numerical models (Bertagnolio, Rasmussen, Sørensen, Johansen, Madsen, 2010). The modeling steps and different models of the WT are detailed in (Ackermann, 2005).

In addition, WTs are generally inaccessible (several meters in height), control and diagnoses are not easy tasks (Amirat, Benbouzid, Al-Ahmar, Bensaker, Turri, 2009). Different signatures can be identified on the operation of the WT, in particular vibration, which can lead to defects such as cracking the motor shaft. Atmospheric conditions can also power deficits, hence the need to stabilize turbulence (Mirecki, Roboam, Richardeau, 2007). These defects must be detected as soon as possible to minimize damage (Hansen, Barthelmie, Jensen, Sommer, 2012) (Margaris, Hansen, Sorensen, Hatziargyriou, 2010). However, the diagnosis procedure is just the first step toward a new synthesis of the control law in which presence of defect is taken into account. The second step is a reconfiguration approach based on information of the FDI module (Fault Detection and Isolation) able to give a new control law and to ensure the stability of the closed loop system, and to guarantee the system performances or their minimal degradation in fault presence: It is the Fault Tolerant Control (FTC) (Tastu, Pinson, Kotwa, Madsen, Nielsen, 2011) (Patton, Putra, Klinkhieo, 2008). A system is called fault tolerant one if it can maintain the design objectives even when there is fault.

The FTC is divided into two approaches: passive and active. In the passive one, regulators are synthesized to be robust to some defects. The main idea is to make the closed loop system robust to incertitude and some specific defects. The weakness of this approach is that its capacity to tolerate defaults remains restricted to some faults only. The active approach has to react to various systems failures in order to preserve the stability and the performance of the system. A fault tolerant control approach, in multi-model, was developed in (Odgaard, and Stoustrup, 2009). Other control laws have been developed using neural networks (Jurado, Saenz, 2002) and other techniques (Beltran, AhmedAli, Benbouzid, 2008).

In the wind power industry, the Doubly Fed Induction Generator (DFIG), with the Permanent Magnet Synchronous Generator (PMSG), is one of the most used electrical machine in WT because of its low cost, its simplicity of maintenance, and its reliability. Nevertheless, the DFIG is not a fault-free system. A defective bearings, windings or electrical insulation can affect the generator.

In previous work (Bennouna, Héraud, Rodriguez, Camblong, 2007), a technique has been developed allowing the diagnosis of the DFIG. This method is based on the polynomial representation of the different variables of the system. Thus, the data are validated when no error is present; otherwise errors are detected, localized, identified then, estimated. This paper presents a Fault Detection and Isolation (FDI) technique dealing with wind turbine. This method is based on the use of Generalized Observer Scheme (GOS) by a bank of Kalman filter, which allows detecting and isolating multiple sensor faults.

The layout of the article is as follows. Section 2 explains the principle of the method GOS for the diagnosis with the use of the Page-Hinkley's test. Section 3 presents the model of the Doubly Fed Induction Generator (D.F.I.G). Tests and results will be investigated in section 4. Section 5 is devoted to the real-time validation using Matlab RTW (Real-Time Workshop) and dSAPCE. Finally, concluding remarks are presented in section 6.

Diagnosis Procedure: GOS Approach

The GOS approach is one of the method to solve the problem of state observer for Fault Detection and Isolation.

In this paper, FDI is done using a GOS approach concerning sensors faults. The state vector is assumed completely observable and there is no uncertainty about the model parameters. The i^{th} observer is driven by all inputs and all outputs except the i^{th}. Thus, the output of this observer will be sensitive to defects in all outputs except the i^{th}.

The observer used in this study is the Kalman filter which allows estimating the state of the system using the model and the inputs.

The dynamic model of discrete systems is given by:

$$\begin{cases} x_{k+1} = A\,x_k + B\,u_k + w_k \\ z_k = H\,x_k + v_k \end{cases} \quad (1)$$

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where $x \in R^n$ is the state, $z \in R^m$ is measurement, and A, B, H are matrices of appropriated dimension. w and v represent the process and measurement noises.

The Kalman filter procedure consists of two steps:

Prediction step:

$$\begin{cases} \hat{x}_k = A\,\hat{x}_{k-1} + B\,u_k \\ P_k = A\,P_{k-1}A^T + Q \end{cases} \tag{2}$$

Correction step:

$$\begin{cases} K_k = P_k H^T (H P_k H^T + R)^{-1} \\ \hat{x}_k = \hat{x}_k + K_k (z_k - H\hat{x}_k) \\ P_k = (I - K_k H) P_k \end{cases} \tag{3}$$

More details about the Kalman filter can be found in (Zarchan, Musoff, 2005).

The state estimation given by the Kalman filter allows defining residual vectors. The Page-Hinkley's test (Basseville, 1986) is subsequently applied in order to detect and isolate the sensors failures. Isolation structure of sensors errors is:

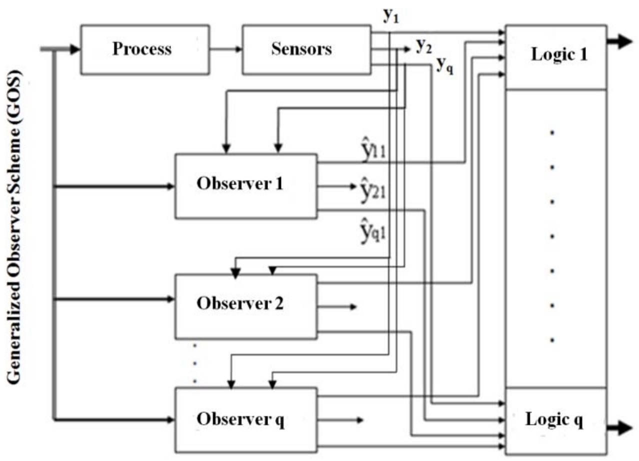

FIG. 1 ISOLATION STRUCTURE OF SENSORS ERRORS

Application

Introduction

In this paper, the application chosen deals with the Doubly Fed Induction Generator (DFIG) of a wind turbine. Indeed, electrical machines are widely used in industry and especially the induction one which is the most robust and cheapest in the market. Since its maintenance is insignificant, its field of use has been extended to advanced fields such as aerospace, chemical or wind turbines. However, despite its robustness, defects could appear, during its lifetime, because of stress.

Progress in power electronics and microelectronics fields; has permitted implementation of efficient control law of this machine. However, many problems remain either at the machine or sensors.

Doubly Fed Induction Generator (DFIG)

The mathematical model of the D.F.I.G in the (α, β) basis is given by (Bennouna, Héraud, 2011):

$$\frac{d}{dt}\begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{pmatrix} = \frac{1}{(L_s L_r - L_h^2)} \begin{pmatrix} -R_s L_r & \omega_m L_h^2 & L_h R_r & \omega_m L_r L_h \\ -\omega_m L_h^2 & -R_s L_r & -\omega_m L_r L_h & L_h R_r \\ L_h R_s & -\omega_m L_s L_h & -R_r L_s & -\omega_m L_s L_r \\ \omega_m L_s L_h & L_h R_s & \omega_m L_s L_r & -R_r L_s \end{pmatrix} \begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{pmatrix} + \frac{1}{(L_s L_r - L_h^2)} \begin{pmatrix} L_r & 0 & -L_h & 0 \\ 0 & L_r & 0 & -L_h \\ -L_h & 0 & L_s & 0 \\ 0 & -L_h & 0 & L_s \end{pmatrix} \begin{pmatrix} u_{\alpha s} \\ u_{\beta s} \\ u_{\alpha r} \\ u_{\beta r} \end{pmatrix} \tag{4}$$

Where:

$i_{\alpha s,\beta s}$, $i_{\alpha r,\beta r}$ are respectively the currents of the stator and the rotor on the phase's alpha and beta.

$u_{\alpha s,\beta s}$, $u_{\alpha r,\beta r}$ are respectively the voltages of the stator and the rotor on the phase's alpha and beta

ω_m is the rotational speed of the generator.

L_s, L_r, L_h are respectively the inductance of the stator, the rotor and the mutual inductance.

R_s, R_r are respectively the resistance of the stator and the rotor.

The (α, β) basis is obtained from the classic basis (a,b,c) using the Park transformation which requires the knowledge of the teta angle.

The model given above can be rewritten in the form of state representation, where:

$$x = \begin{pmatrix} i_{\alpha s} \\ i_{\beta s} \\ i_{\alpha r} \\ i_{\beta r} \end{pmatrix} \quad u = \begin{pmatrix} u_{\alpha s} \\ u_{\beta s} \\ u_{\alpha r} \\ u_{\beta r} \end{pmatrix}$$

$$B = \frac{1}{(L_s L_r - L_h^2)} \begin{pmatrix} L_r & 0 & -L_h & 0 \\ 0 & L_r & 0 & -L_h \\ -L_h & 0 & L_s & 0 \\ 0 & -L_h & 0 & L_s \end{pmatrix}$$

$$A = \frac{1}{(L_s L_r - L_h^2)} \begin{pmatrix} -R_s L_r & \omega_m L_h^2 & L_h R_r & \omega_m L_r L_h \\ -\omega_m L_h^2 & -R_s L_r & -\omega_m L_r L_h & L_h R_r \\ L_h R_s & -\omega_m L_s L_h & -R_r L_s & -\omega_m L_s L_r \\ \omega_m L_s L_h & L_h R_s & \omega_m L_s L_r & -R_r L_s \end{pmatrix}$$

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Tests & Results

Tests Structure

First tests were achieved using the numeric simulator (Matlab/Simulink). A full representation of a wind turbine with a D.F.I.G was created, as shown next:

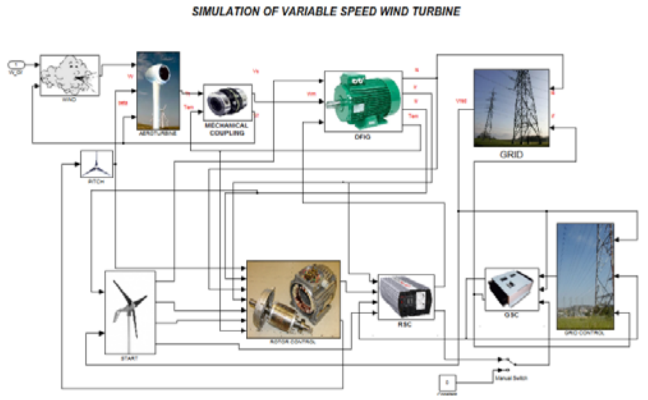

FIG. 2 GENERAL REPRESENTATION OF A WIND TURBINE USING MATLAB / SIMULINK

The diagnosis procedure is given in the following figure:

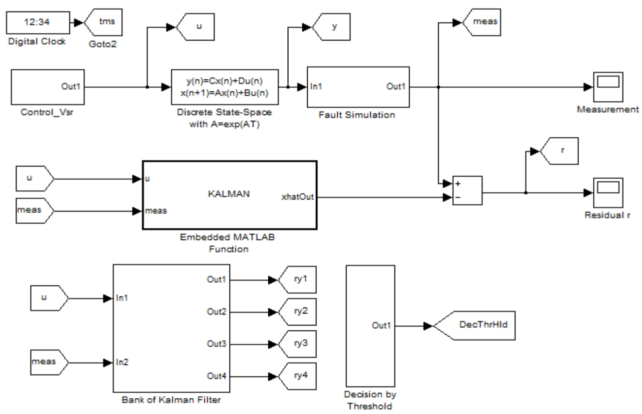

FIG. 3 DIAGNOSIS PROCEDURE

The generalized observer scheme for fault detection and isolation by a bank of Kalman filter is:

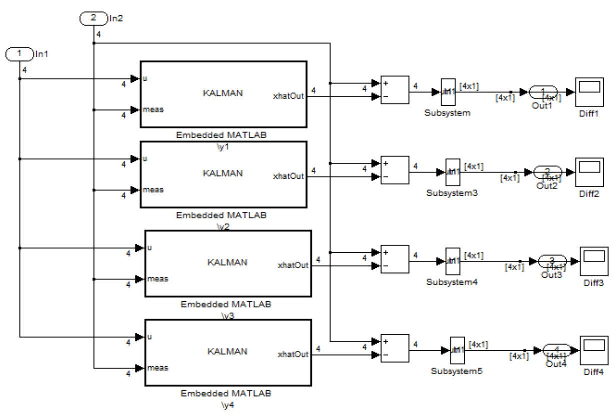

FIG. 4 THE GOS FOR FDI BY A BANK OF KAMAN FILTER

This scheme consists of several blocks: the system model as a discrete state representation, the fault simulation, the bank of Kalman filter and the decision.

An experimental benchmark was also used composed of a DC machine of 25 kW emulating the aerodynamic and mechanical behaviour of the wind, and a D.F.I.G of 15 kW playing the role of the electric machine.

This system constitutes an intermediate stage between tests on the numeric simulator (Matlab/Simulink) and a real wind turbine.

FIG. 5 THE EXPERIMENTAL BENCHMARK

The control of the electric machines is done by using Digital Signal Processors (DSP). Digital- to- analogue and analogue- to- digital converters assure the communication between these DSP and the electronic components of the system. The DSP of the DC machine sends a reference of the electromagnetic torque to the DSP of the D.F.I.G by using their inputs and outputs and converters.

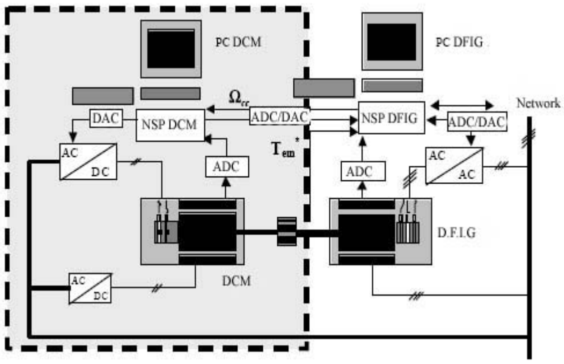

FIG. 6 COMPOSITION OF EXPERIMENTAL BENCHMARK

Figure 6 shows the composition of the experimental system. All the components are:

- DCM: is the DC machine, whose role is to emulate the aerodynamic and mechanical behaviour of the wind.
- PC DCM and NSP DCM: the NSP of the DCM contains the simulation's model and the equations of the DCM.

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- DFIG: plays the role of the generator of the wind turbine.
- PC DFIG: the DFIG is connected to the network by a magnetizing, then a synchronisation of the electric variables of the network and the stator of the DFIG.

Several tests were carried out according to three kinds of defects: additive, multiplicative and loose of sensor.

Results

An error of 20% is multiplied to the rotor current on alpha phase $i_{\alpha r}$ from the sample 250. Figure 7 represents the four currents.

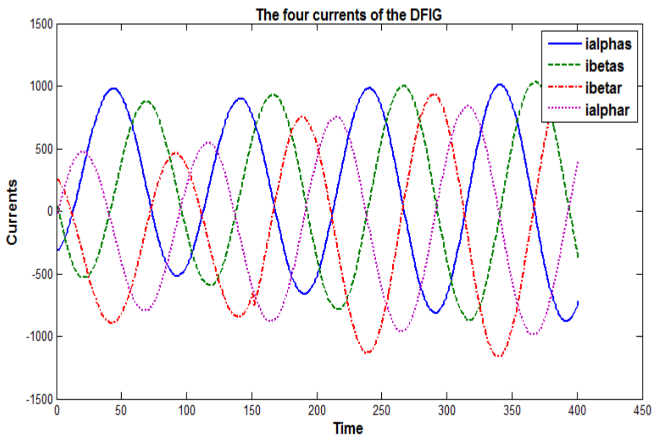

FIG. 7 THE FOUR CURRENTS OF THE DFIG

From the above figure, it is unable to detect if there is a problem on the DFIG. Nevertheless, the residues of the four state variables, given in figure 8, show that there is a problem in the generator without localizing it.

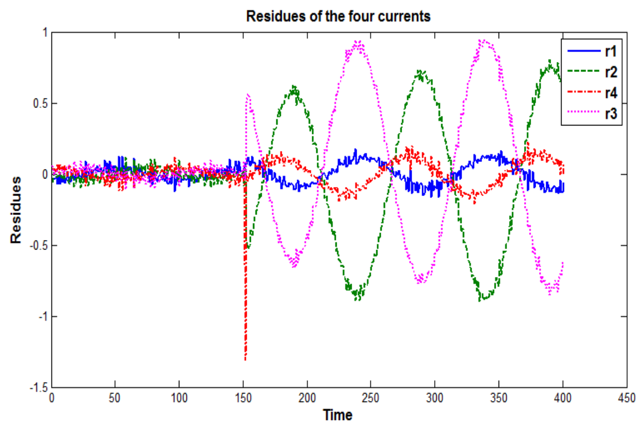

FIG. 8 RESIDUES OF THE FOUR CURRENTS OF THE DFIG

The advantage of using a GOS structure is not only to detect but also to localize the defect. Thus, in our case, the results corresponding to residues of the four observers are given in figure 9.

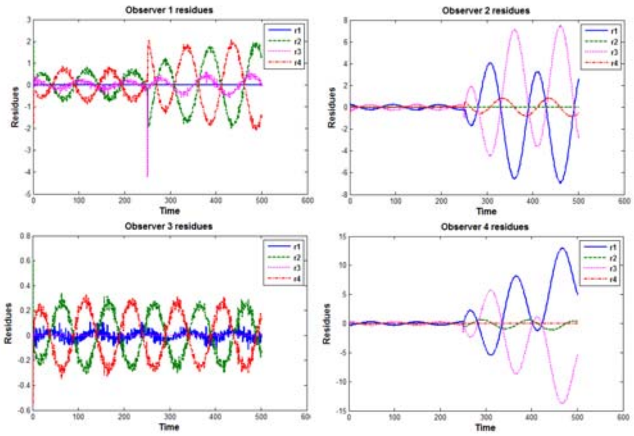

FIG. 9 RESIDUES OF THE GOS STRUCTURE

Using a logical decision, we can easily find the suspected variable. In this case, it is indeed the rotor current on alpha phase $i_{\alpha r}$. The occurrence time of the defect can also be known, as shown in the following figure:

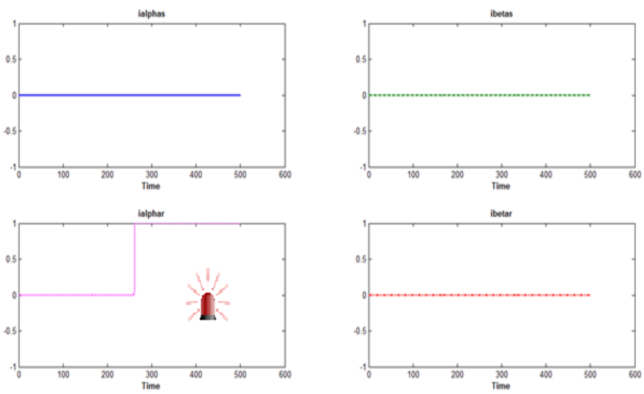

FIG. 10 FAULT DETECTION OF THE SUSPECTED VARIABLE

Real Time Tests

The work presented in this paper was validated on a test bench, which is based on a dSPACE DS1006 processor board. This board dispose of an AMD Opteron processor clocked at 2.6 Ghz.

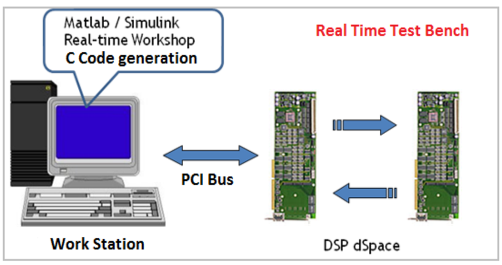

FIG. 11 REAL-TIME TEST BENCH

The Simulink's model of the DFIG and the fault detection procedure were translated in C code using Matlab Real-Time Workshop then downloaded to the test bench. The result of the FDI processus was displayed on LEDs of the dSPACE DS4002 card. This

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validation indicated that our approach can be used in a real-time environment.

Conclusions

A technique of fault detection has been presented in this paper based on the use of a Generalized Observer Scheme. This method is applied to a Doubly Fed Induction Generator of a wind turbine using an experimental benchmark. Results show that the proposed fault diagnosis method can detect and localize three kinds of errors: additive, multiplicative and loose of sensor. However, this technique cannot be used in the case of presence of multiple faults.

Our next work will focus on use of the Dedicated Observer Scheme which allows detecting and isolating the simultaneous sensor faults as well as the comparison of proposed observer scheme performance with other ones. Other FDI problems dealing with the mechanical coupling will be studied.

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